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A short proof that adding some permutation rules to β preserves SN

René David
LAMA - Equipe LIMD - Université de Chambéry
e-mail : rene.david@univ-savoie.fr

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Abstract

I show that, if a term is SN for β , it remains SN when some permutation rules are added.

1 Introduction

Strong normalization (abbreviated as SN) is a property of rewriting systems that is often desired. Since about 10 years many researchers have considered the following question : If a λ -term is SN for the β -reduction, does it remain SN if some other reduction rules are added ? They are mainly interested with permutation rules they introduce to be able to delay some β -reductions in, for example, *let* $x = \dots$ *in* \dots constructions or in *calculi with explicit substitutions*. Here are some papers considering such permutations rules: L. Regnier [7], F Kamareddine [3], E. Moggi [5], R. Dyckhoff and S. Lengrand [2], A. J. Kfoury and J. B. Wells [4], Y. Ohta and M. Hasegawa [6], J. Esprito Santo [8] and [9].

Most of these papers show that SN is preserved by the addition of the permutation rules they introduce. But these proofs are quite long and complicated or need some restrictions to the rule. For example the rule $(M (\lambda x.N P)) \triangleright (\lambda x.(M N) P)$ is often restricted to the case when M is an abstraction (in this case it is usually called *assoc*).

I give here a very simple proof that the permutations rules preserve SN when they are added all together and with no restriction. It is done as follows. I show that every term which is typable in the system (often called system \mathcal{D}) of types built with \rightarrow and \wedge is strongly normalizing for all the rules (β and the permutation rules). Since it is well known that a term is SN for the β -rule iff it is typable in this system, the result follows.

2 Definitions and notations

Definition 2.1 • The set of λ -terms is defined by the following grammar

$$\mathcal{M} ::= x \mid \lambda x.\mathcal{M} \mid (\mathcal{M} \mathcal{M})$$

- The set \mathcal{T} of types is defined by the following grammar where \mathcal{A} is a set of atomic constants

$$\mathcal{T} ::= \mathcal{A} \mid \mathcal{T} \rightarrow \mathcal{T} \mid \mathcal{T} \wedge \mathcal{T}$$

- The typing rules are the following :

$$\begin{array}{c}
\overline{\Gamma, x : A \vdash x : A} \\
\\
\frac{\Gamma \vdash M : A \rightarrow B \quad \Gamma \vdash N : A}{\Gamma \vdash (M N) : B} \quad \frac{\Gamma, x : A \vdash M : B}{\Gamma \vdash \lambda x. M : A \rightarrow B} \\
\\
\frac{\Gamma \vdash M : A \wedge B}{\Gamma \vdash M : A} \quad \frac{\Gamma \vdash M : A \wedge B}{\Gamma \vdash M : B} \\
\\
\frac{\Gamma \vdash M : A \quad \Gamma \vdash M : B}{\Gamma \vdash M : A \wedge B}
\end{array}$$

Definition 2.2 The reduction rules are the following.

- $\beta : (\lambda x. M N) \triangleright M[x := N]$
- $\delta : (\lambda y. \lambda x. M N) \triangleright \lambda x. (\lambda y. M N)$
- $\gamma : (\lambda x. M N P) \triangleright (\lambda x. (M P) N)$
- $assoc : (M (\lambda x. N P)) \triangleright (\lambda x. (M N) P)$

Using Barendregt's convention for the names of variables, we assume that, in γ (resp. δ , $assoc$), x is not free in P (resp. in N , in M).

The rules δ and γ have been introduced by Regnier in [7] and are called there the σ -reduction. It seems that the first formulation of $assoc$ appears in Moggi [5] in the restricted case where M is an abstraction and in a “let ... in ...” formulation.

Notation 2.1 • If t is a term, $size(t)$ denotes its size and $type(t)$ the size of its type. If $t \in SN$ (i.e. every sequence of reductions starting from t is finite), $\eta(t)$ denotes the length of the longest reduction of t .

- Let σ be a substitution. We say that σ is fair if the $\sigma(x)$ for $x \in dom(\sigma)$ all have the same type (that will be denoted as $type(\sigma)$). We say that $\sigma \in SN$ if, for each $x \in dom(\sigma)$, $\sigma(x) \in SN$.
- Let $\sigma \in SN$ be a substitution and t be a term. We denote by $size(\sigma, t)$ (resp. $\eta(\sigma, t)$) the sum, over $x \in dom(\sigma)$, of $nb(t, x).size(\sigma(x))$ (resp. $nb(t, x).\eta(\sigma(x))$) where $nb(t, x)$ is the number of occurrences of x in t .
- If \vec{M} is a sequence of terms, $lg(\vec{M})$ denotes its length, $M(i)$ denotes the i -th element of the sequence and $tail(\vec{M})$ denotes \vec{M} from which the first element has been deleted.
- Assume $t = (H \vec{M})$ where H is an abstraction or a variable and $lg(\vec{M}) \geq 1$.
 - If H is an abstraction (in this case we say that t is β -head reducible), then $M(1)$ will be denoted as $Arg[t]$ and $(R' tail(\vec{M}))$ will be denoted by $B[t]$ where R' is the reduct of the β -redex $(H Arg[t])$.
 - If $H = \lambda x. N$ and $lg(\vec{M}) \geq 2$ (in this case we say that t is γ -head reducible), then $(\lambda x. (N M(2)) M(1) M(3) \dots M(lg(\vec{M})))$ will be denoted by $C[t]$.
 - If $H = \lambda x. \lambda y. N$ (in this case we say that t is δ -head reducible), then $(\lambda y. (\lambda x. N M(1)) M(2) \dots M(lg(\vec{M})))$ will be denoted by $D[t]$.

- If $M(i) = (\lambda x. N P)$, then the term $(\lambda x. (H M(1) \dots M(i-1) N) P M(i+1) \dots M(\lg(\vec{M})))$ will be denoted by $A[t, i]$ and we say that $M(i)$ is the redex put in head position.

- Finally, in a proof by induction, *IH* will denote the induction hypothesis.

3 The theorem

Theorem 3.1 *Let t be a term. Assume t is strongly normalizing for β . Then t is strongly normalizing for β, δ, γ and *assoc*.*

Proof This follows immediately from Theorem 3.2 and corollary 3.1 below. \square

Theorem 3.2 *A term is SN for the β -rule iff it is typable in system \mathcal{D} .*

Proof This is a classical result. For the sake of completeness I recall here the proof of the only if direction given in [1]. Note that it is the only direction that is used in this paper and that corollary 3.1 below actually gives the other direction. The proof is by induction on $\langle \eta(t), \text{size}(t) \rangle$.

- If $t = \lambda x. u$. This follows immediately from the IH.
- If $t = (x v_1 \dots v_n)$. By the IH, for every j , let $x : A_j, \Gamma_j \vdash v_j : B_j$. Then $x : \bigwedge A_j \wedge (B_1, \dots, B_n \rightarrow C), \bigwedge \Gamma_j \vdash t : C$ where C is any type, for example any atomic type.
- If $t = (\lambda x. a \ b \ \vec{c})$. By the IH, $(a[x := b] \ \vec{c})$ is typable. If x occurs in a , let $A_1 \dots A_n$ be the types of the occurrences of b in the typing of $(a[x := b] \ \vec{c})$. Then t is typable by giving to x and b the type $A_1 \wedge \dots \wedge A_n$. Otherwise, by the induction hypothesis b is typable of type B and then t is typable by giving to x the type B . \square

From now on, \triangleright denotes the reduction by one of the rules β, δ, γ and *assoc*.

Lemma 3.1 1. *The system satisfies subject reduction i.e. if $\Gamma \vdash t : A$ and $t \triangleright t'$ then $\Gamma \vdash t' : A$.*

2. *If $t \triangleright t'$ then $t[x := u] \triangleright t'[x := u]$.*

3. *If $t' = t[x := u] \in SN$ then $t \in SN$ and $\eta(t) \leq \eta(t')$.*

Proof Immediate. \square

Lemma 3.2 *Let $t = (H \ \vec{M})$ be such that H is an abstraction or a variable and $\lg(\vec{M}) \geq 1$. Assume that*

1. *If t is δ -head reducible (resp. γ -head reducible, β -head reducible), then $D[t] \in SN$ (resp. $C[t] \in SN, Arg[t], B[t] \in SN$).*

2. *For each i such that $M(i)$ is a redex, $A[t, i] \in SN$,*

Then $t \in SN$.

Proof By induction on $\eta(H) + \sum \eta(M(i))$. Show that each reduct of t is in SN . \square

Lemma 3.3 *If $(t \ \vec{u}) \in SN$ then $(\lambda x. t \ x \ \vec{u}) \in SN$.*

Proof This is a special case of the following result. If $t \in SN$ then so is $F(t)$ where $F(t)$ is obtained in the following way: choose a node on the left branch of t and replace the sub-term u at this node by $(\lambda x. u \ x)$. The proof is by induction on $\langle \text{type}(u), \eta(t), \text{size}(t) \rangle$, using Lemma 3.2. The only non immediate cases are when the head redex has been created by the transformation F . The case of β is trivial. For δ and γ , the result follows from the fact that the type of the sub-term modified has decreased and there is nothing to prove for *assoc* since the change is in the left branch. \square

Theorem 3.3 *Let $t \in SN$ and $\sigma \in SN$ be a fair substitution. Then $\sigma(t) \in SN$.*

Proof By induction on $\langle \text{type}(\sigma), \eta(t), \text{size}(t), \eta(\sigma, t), \text{size}(\sigma, t) \rangle$. If t is an abstraction or a variable the result is trivial. Thus assume $t = (H \vec{M})$ where H is an abstraction or a variable and $n = \text{lg}(\vec{M}) \geq 1$. Let $\vec{N} = \sigma(\vec{M})$.

Claim: Let \vec{P} be a (strict) initial or a final sub-sequence of \vec{N} . Then $(z \vec{P}) \in SN$.

Proof: This follows immediately from Lemma 3.1 and the IH. \square

We use Lemma 3.2 to show that $\sigma(t) \in SN$.

1. Assume $\sigma(t)$ is δ -head reducible. We have to show that $D[\sigma(t)] \in SN$. There are 3 cases to consider.
 - (a) If t was already δ -head reducible, then $D[\sigma(t)] = \sigma(D[t])$ and the result follows from the IH.
 - (b) If H is a variable and $\sigma(H) = \lambda x. \lambda y. a$, then $D[\sigma(t)] = t'[z := \lambda y. (\lambda x. a \ N(1))]$ where $t' = (z \ \text{tail}(\vec{N}))$. By the claim, $t' \in SN$ and since $\text{type}(z) < \text{type}(\sigma)$ it is enough to check that $\lambda y. (\lambda x. a \ N(1)) \in SN$. But this is $\lambda y. (z' \ N(1))[z' := \lambda x. a]$. But, by the claim, $(z' \ N(1)) \in SN$ and we conclude by the IH since $\text{type}(z') < \text{type}(\sigma)$.
 - (c) If $H = \lambda x. z$ and $\sigma(z) = \lambda y. a$, then $D[\sigma(t)] = (\lambda y. (\lambda x. a \ N(1)) \ \text{tail}(\vec{N})) = \tau(t')$ where $t' = (z' \ \text{tail}(\vec{M}))$ and τ is the same as σ on the variables of $\text{tail}(\vec{M})$ and $\tau(z') = \lambda y. (\lambda x. a \ N(1))$. By the IH, it is enough to show that $(\lambda x. a \ N(1)) \in SN$. But this is $(\lambda x. z'' \ N(1))[z'' := a]$ and, since $\text{type}(a) < \text{type}(\sigma)$ it is enough to show that $u = (\lambda x. z'' \ N(1)) = \sigma'(t'') \in SN$ where t'' is a sub-term of t (up to the renaming of z into z'') and σ' is as σ but $z'' \notin \text{dom}(\sigma')$. This follows from the IH since $\text{size}(\sigma', t'') < \text{size}(\sigma, t)$.
2. Assume $\sigma(t)$ is γ -head reducible. We have to show that $C[\sigma(t)] \in SN$. There are 4 cases to consider.
 - (a) If H is an abstraction, then $C[\sigma(t)] = \sigma(C[t])$ and the result follows immediately from the IH.
 - (b) H is a variable and $\sigma(H) = \lambda y. a$, then $C[\sigma(t)] = (\lambda y. (a \ N(2)) \ N(1) \ N(3) \dots N(n)) = (\lambda y. (a \ N(2)) \ y \ N(3) \dots N(n))[y := N(1)]$. Since $\text{type}(N(1)) < \text{type}(\sigma)$, it is enough, by the IH, to show $(\lambda y. (a \ N(2)) \ y \ N(3) \dots N(n)) \in SN$ and so, by Lemma 3.3, that $u = (a \ N(2) \ N(3) \dots N(n)) \in SN$. By the claim, $(z \ \text{tail}(\vec{N})) \in SN$ and the result follows from the IH since $u = (z \ \text{tail}(\vec{N}))[z := a]$ and $\text{type}(a) < \text{type}(\sigma)$.
 - (c) H is a variable and $\sigma(H) = (\lambda y. a \ b)$, then $C[\sigma(t)] = (\lambda y. (a \ N(1)) \ b \ N(2) \dots N(n)) = (z \ \text{tail}(\vec{N}))[z := (\lambda y. (a \ N(1)) \ b)]$. Since $\text{type}(z) < \text{type}(\sigma)$, by the IH it is enough to show that $u = (\lambda y. (a \ N(1)) \ b) \in SN$. We use Lemma 3.2.
 - We first have to show that $B[u] \in SN$. But this is $(a[y := b] \ N(1))$ which is in SN since $u_1 = (a[y := b] \ \vec{N}) \in SN$ since $u_1 = \tau(t_1)$ where t_1 is the same as t but where we have given to the variable H the fresh name z , τ is the same as σ for the variables in $\text{dom}(\sigma)$ and $\tau(z) = a[y := b]$ and thus we may conclude by the IH since $\eta(\tau, t) < \eta(\sigma, t)$.
 - We then have to show that, if b is a redex say $(\lambda z. b_1 \ b_2)$, then $A[u, 1] = (\lambda z. (\lambda y. a \ N(1) \ b_1) \ b_2) \in SN$. Let $u_2 = \tau(t_2)$ where t_2 is the same as t but where we have given to the variable H the fresh name z , τ is the same as σ for the variables in $\text{dom}(\sigma)$ and $\tau(z) = \sigma(A[H, 1])$. By the IH, $u_2 \in SN$.

But $u_2 = (\lambda z. (\lambda y. a \ b_1) \ b_2 \ \vec{N})$ and thus $u_3 = (\lambda z. (\lambda y. a \ b_1) \ b_2 \ N(1)) \in SN$. Since u_3 reduces to $A[u, 1]$ by using twice by the γ rule, it follows that $A[u, 1] \in SN$.

- (d) If H is a variable and $\sigma(H)$ is γ -head reducible, then $C[\sigma(t)] = \tau(t')$ where t' is the same as t but where we have given to the variable H the fresh name z and τ is the same as σ for the variables in $dom(\sigma)$ and $\tau(z) = \sigma(C[H])$. The result follows then from the IH.
3. Assume that $\sigma(t)$ is β -head reducible. We have to show that $Arg[\sigma(t)] \in SN$ and that $B[\sigma(t)] \in SN$. There are 3 cases to consider.
- (a) If H is an abstraction, the result follows immediately from the IH since then $Arg[\sigma(t)] = \sigma(Arg[t])$ and $B[\sigma(t)] = \sigma(B[t])$.
 - (b) If H is a variable and $\sigma(H) = \lambda y. v$ for some v . Then $Arg[\sigma(t)] = N(1) \in SN$ by the IH and $B[\sigma(t)] = (v[y := N(1)] \ tail(\vec{N})) = (z \ tail(\vec{N}))[z := v[y := N(1)]]$. By the claim, $(z \ tail(\vec{N})) \in SN$. By the IH, $v[y := N(1)] \in SN$ since $type(N(1)) < type(\sigma)$. Finally the IH implies that $B[\sigma(t)] \in SN$ since $type(v) < type(\sigma)$.
 - (c) H is a variable and $\sigma(H) = (R \ \vec{M'})$ where R is a β -redex. Then $Arg[\sigma(t)] = Arg[\sigma(H)] \in SN$ and $B[\sigma(t)] = (R' \ \vec{M'} \ \vec{N})$ where R' is the reduct of R . But then $B[\sigma(t)] = \tau(t')$ and t' is the same as t but where we have given to the variable H the fresh name z and τ is the same as σ for the variables in $dom(\sigma)$ and $\tau(z) = (R' \ \vec{M'})$. We conclude by the IH since $\eta(\tau, t') < \eta(\sigma, t)$.
4. We, finally, have to show that, for each i , $A[\sigma(t), i] \in SN$. There are again 3 cases to consider.
- (a) If the redex put in head position is some $N(j)$ and $M(j)$ was already a redex. Then $A[\sigma(t), i] = \sigma(A[t, j])$ and the result follows from the IH.
 - (b) If the redex put in head position is some $N(j)$ and $M(j) = (x \ a)$ and $\sigma(x) = \lambda y. b$ then $A[\sigma(t), i] = \lambda y. (\sigma(H) \ N(1) \ \dots \ N(j-1) \ b) \ \sigma(a) \ N(j+1) \ \dots \ N(n)$. Since $type(\sigma(a)) < type(\sigma)$ it is enough, by the IH, to show that $\lambda y. (\sigma(H) \ N(1) \ \dots \ N(j-1) \ b) \ y \ N(j+1) \ \dots \ N(n)$ and so, by Lemma 3.3, that $(\sigma(H) \ N(1) \ \dots \ N(j-1) \ b \ N(j+1) \ \dots \ N(n)) \in SN$. Since $type(b) < type(\sigma)$ it is enough to show $u = (\sigma(H) \ N(1) \ \dots \ N(j-1) \ z \ N(j+1) \ \dots \ N(n)) \in SN$. Let $t' = (H \ \vec{M'})$ where $\vec{M'}$ is defined by $M'(k) = M(k)$, for $k \neq j$, $M'(j) = z$. Since $t = t'[z := (x \ a)]$ and $u = \sigma(t')$ the result follows from Lemma 3.1 and the IH.
 - (c) If, finally, H is a variable, $\sigma(H) = (H' \ \vec{M'})$ and the redex put in head position is some $M'(j)$. Then, $A[\sigma(t), i] = \tau(A[t', j])$ where t' is the same as t but where we have given to the variable H the fresh variable z and τ is the same as σ for the variables in $dom(\sigma)$ and $\tau(z) = A[\sigma(H), j]$. We conclude by the IH since $\eta(\tau, t') < \eta(\sigma, t)$.

□

Corollary 3.1 *Let t be a typable term. Then t is strongly normalizing.*

Proof By induction on $size(t)$. If t is an abstraction or a variable the result is trivial. Otherwise $t = (u \ v) = (x \ y)[x := u][y := v]$ and the result follows immediately from Theorem 3.3 and the IH. □

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